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APPLICATION NUMBER: ***60/490,580***
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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No. EV 292390795 US

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
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Additional inventors are being named on the ______ separately numbered sheets attached hereto

TITLE OF THE INVENTION (500 characters max)

VERTICAL COMB DRIVE AND USES THEREOF

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ENCLOSED APPLICATION PARTS *(check all that apply)*

- ☑ Specification *Number of Pages* 8
- ☑ Drawing(s) *Number of Sheets* 2
- ☐ Application Data Sheet. See 37 CFR 1.76
- ☐ CD(s), Number
- ☑ Other (specify) 1. Check in the amount of $80.00 2. Acknowledgement Postcard

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

- ☑ Applicant claims small entity status. See 37 CFR 1.27.
- ☑ A check or money order is enclosed to cover the filing fees.
- ☑ The Director is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number: 50-1529
- ☐ Payment by credit card. Form PTO-2038 is attached.

FILING FEE AMOUNT ($): $80.00

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

- ☑ No.
- ☐ Yes, the name of the U.S. Government agency and the Government contract number are: ______

Respectfully submitted,

SIGNATURE William H. Dippert

Date 7/28/03

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REGISTRATION NO. *(If appropriate)* 26,723

Docket Number: 501012.20539

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USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

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Applicant: Matan Naftali et al.
Serial No: Not yet assigned
Filing Date: July 28, 2003 herewith
For: VERTICAL COMB DRIVE AND USES THEREOF
Enclosure: (1) Provisional Application Cover Sheet (1 page); (2) Specification (8 pages); (3) Drawings (2 sheets); (4) Check in the amount of $80.00; (5) Acknowledgement postcard

VERTICAL COMB DRIVE AND USES THEREOF

FIELD OF THE INVENTION

The invention relates to Micro-Optical-Electro-Mechanical-Systems (MOEMS) devices and specifically to micro mirrors. More particularly, the present invention discloses solutions for the three following problems: 1) fabrication of vertical comb-drives with self alignment, using a single device layer and a single machining process; 2) achieving a linear response in an angular, vertical comb-drive actuator; 3) producing a triangular displacement waveform in resonant response, with tunable resonance frequency.

BACKGROUND OF THE INVENTION

Many state-of-the-art electrostatic actuators with an angular degree of freedom (e.g., tilting micromirrors) are driven by electrostatic forces. These systems are constructed from a moving part (henceforth rotor) and static parts (stators) that apply driving forces on the rotor. Such a system may be a rigid plate (rotor) suspended by a torsion bar over fixed electrodes (stators) that are parallel to the rotor. This configuration is in essence a generalization of a parallel-plates actuator, and it suffers from similar nonlinearity and instabilities. The nonlinearity and instabilities that characterize the axial motion of the parallel-plates actuator can be avoided by using a double-sided comb-drive actuator to achieve a stable axial motion. This device enables in-plane motion with a linear response.

Vertical comb-drive actuators (VCD) attempt to generalize the working principle of the double-sided comb-drive actuator to angular motion]. However, the response of current state-of-the-art vertical comb-drive actuators is not linear. Moreover, current state-of-the-art fabrication methods for VCDs require complex and expensive micromachining processes.

This present invention discloses a novel fabrication process of vertical comb-drives with self-alignment, characterized by a single device layer and a single machining process. Furthermore, the present invention introduces a VCD with a linear angular response.

Many scanning and display applications require a "saw tooth" waveform, or a triangular waveform, of the angular motion. Current methods for generating a “saw tooth” waveform are difficult to implement in MOEMS technology. Furthermore, in these methods, it is difficult to adjust and tune the resonance frequency. The present invention discloses a novel scheme for generating a triangular displacement waveform in resonant response, with tunable resonance frequency.

Many novel MOEMS applications require tilting motion of a deformable element. A common means of achieving such a tilting motion is suspending a rigid plate-electrode on a torsion beam above a driving counter-electrode. This configuration is in essence a generalization of a parallel-plates actuator. However, this actuation scheme suffers from a nonlinear electromechanical response and an inherent instability that decreases the controllable range of the device.

One means of eliminating these difficulties in electrostatic tilting actuators, is to use vertical comb drives. In a vertical comb drive, two sets of combs - the stator comb and the rotor comb - are staggered in a vertical orientation such that they can slide one into the other. The two combs constitute a free space capacitor, and the motion between them changes the capacity of the free-space capacitor they form. Accordingly, when a voltage difference is applied between the stator and rotor combs, a vertical electrostatic force is induced that can be utilized to generate vertical motion.

One motivation of using vertical comb drives, for tilting deformable elements, is to achieve a linear relation between the driving voltage and the induced angular motion. However, such a linear response is not trivially achieved, and current vertical comb drives do not have this capability.

Furthermore, proper operation of vertical comb drives requires that the stator and rotor combs be perfectly aligned. Misalignment of the stator and rotor combs may give rise to the unwarranted "side pull-in" phenomenon. To overcome the side pull-in, the suspending structure must be made stiffer, resulting in excessive increase of the required driving voltage.

Achieving a perfectly aligned VCD, requires fabrication of the entire VCD out of a single silicon layer. In this way, the VCD has a natural self-alignment. The current state-of-the-art fabrication methods of self-aligned VCDs comprise of a sequence of several photo-lithography and etching steps. Implementation of these methods is complex and expensive.

For some optical MEMS applications, motion of reflective elements is required to be not only linear but periodic (e.g., scanning and rasterring applications). In these applications it a "saw tooth" wave-form for the motion is desired. A well known method of generating a "saw tooth" wave-form is summing the first, third and fifth harmonies of a sine series. However, the implementation of this method is very complex as it requires simultaneous actuation in three different degrees of freedom, with perfect tuning of the different frequencies and phases.

DETAILED DESCRIPTION OF THE PRESENT INVENTION

The novelties of the present invention are:

1) Fabrication of vertical comb-drives with self alignment, using a single device layer and a single machining process. This innovation simplifies the fabrication process (e.g., a single machining process rather than a few machining processes), thus reduces the cost of fabrication.

2) Achieving a linear response in an angular, vertical comb-drive actuator. Previous art has failed to achieve such a linear response.

3) Producing a triangular displacement waveform in resonant response, with tunable resonance frequency. This innovation enables to tune the resonance frequency without any post fabrication modifications, by varying the amplitude of a single voltage source.

The present invention has several advantages over the conventional solutions to the problems described above.

1) Fabrication of vertical comb-drives using a single device layer and a single machining process is less complex, thus more cost effective. Moreover, by using only a single device layer, the VCD has a natural self-alignment between the stator and the rotor combs. Therefore, the side pull-in phenomenon is diminished.

2) A linear response of an angular, vertical comb-drive actuator enables an optimal open-loop control of the angular motion. Nonlinear relation between the tilting angle and the driving voltage requires a feedback to control the motion. Feedback control implementation is both more complicated and expensive than the open-loop control. Moreover, the response of nonlinear devices is more sensitive to fabrication tolerances.

3) Producing a triangular displacement waveform in resonant response, with tunable resonance frequency enables to tune the optimal operation frequency without any post-fabrication modifications. The operation frequency of current state-of-the-art methods for achieving triangular waveforms is fixed and set by the device geometry. Thus, in the state-of-the-art it is very difficult to modify the resonance frequency, and the minute modifications that can be achieved require post-fabrication adjustments (e.g., laser trimming).

In state-of-the-art angular VCD actuators, the rotor is suspended on a flexible torsion bar that enables the angular motion. The present invention discloses a simple process that enables fabrication of vertical comb-drives with self-alignment, using a single device layer and a single machining process.

In accordance with a preferred embodiment of the present invention, the stator combs are fabricated in the *same* layer and *same* process as the rotor, and like the rotor, they are *also suspended* on flexible supports (Fig. 1a, Fig. 1b). This is in contrast with common VCDs in which the stators are fabricated in their fixed final position. The flexible supports of the stators enable to lower or elevate the stators into the desired position after the micromachining process. This allows fabricating the stators in the same level as the rotor, and repositioning them into an optimal location relative to the rotor after the microfabrication.

This post-fabrication repositioning of the stators is a mechanical process achieved by application of the required forces. The repositioning may be an angular repositioning as in the device described in Fig. 1a, or an axial repositioning as in the device described in Fig. 1b. The stators can then be locked into their new position by various means (e.g., using isolating glue). By forcing the stator against displacement limiters before locking them into their final position, alignment between the rotor and stators is achieved.

In the current state-of-the-art angular VCD actuators, the relation between the tilting angle and the driving voltage is nonlinear. In these VCDs, the rotor's torsion bar is as thick as the rotor's layer (Fig. 2). Therefore, the axis of rotation is located in the middle of the device layer. Due to this axis location, the relation between the varying rotor voltage and the rotor angle is nonlinear.

The present invention discloses a simple scheme of achieving a linear response of the VCD. The linear response is achieved by 1) locating the axis of rotation at the surface of the rotor that is engaged with the stator (Fig. 3a,b); 2) using local thickening of the stator comb fingers (Fig. 4). This thickening is also used to reduce the effect of unwarranted actuation of secondary degrees of freedom.

The response of rotating elements (for example micro mirrors) at resonance frequency is sinusoidal. By using a flexible suspension with nonlinear kinematic-dependent rigidity, this response is converted into a triangular waveform. As the torsion bar of the rotating element is tilting at the maximum desired angle, it makes contact with an angle limiter (i.e., "stopper"). Consequently, the effective length of its suspension is reduced (Fig.7), and therefore the rigidity of the suspension is increased. As long as this contact is maintained the motion is referred to as confined motion.

The contact moment that develops between the stoppers and the rotor (Fig. 6a, Fig. 6b), rapidly decrease the angular velocity of the rotor. Eventually, the angular velocity is reversed and the suspension separates from the stoppers to regain free motion in the opposite direction.

A triangular waveform of motion is achieved by kinematically cropping the sinusoidal free-motion. This cropping is achieved by the contact with the stoppers. The remaining portion of the sinusoidal free motion is nearly linear. Due to the rapid velocity reversal, the waveform of the motion approaches a triangular form.

The motion frequency depends on the ratio between the time interval of free motion and the time interval of confined motion. Therefore, the faster the rotor rotates, the more time of confined motion is required to reverse the rotor velocity, and less time is required to cover the free motion. Thus, the motion frequency depends on the overall energy of the system. By controlling the amount of energy (i.e., by controlling the amplitude of the applied driving voltage) the motion frequency can be tuned.

The driving voltages are sequentially switched to achieve the periodic tilting of the suspended mirror. To ensure that the system operates at a resonance, the switching frequency of the driving voltage must equal the angular frequency of the tilting micromirror. This is achieved by synchronizing the switching with the contact occurrences, or by other means (e.g., capacitance sensors, maximum tilt angle sensors).

It should be clear that the description of the embodiments and attached Figures set forth in this specification serves only for a better understanding of the invention, without limiting its scope.

It should also be clear that a person skilled in the art, after reading the present specification could make adjustments or amendments to the attached Figures and above described embodiments that would still be covered by the scope of the present invention.

CLAIMS

1. A method for manufacturing a vertical comb driver comprising fabricating stator combs and rotor combs simultaneously in a single layer of substrate.

2. A method for achieving a linear relation between the driving rotor voltage and the rotor tilt angle.

3. A method for generating a triangular waveform of the angular motion of an actuator with a tunable resonance frequency.

Title:	Vertical Comb Drive And Uses Thereof
Inventor(s):	Matan Naftali, et al.
Appl. No.:	To Be Assigned
Filing Date:	July 28, 2003, herewith
Docket No.:	501012.2053
Sheet No.:	1 of 2

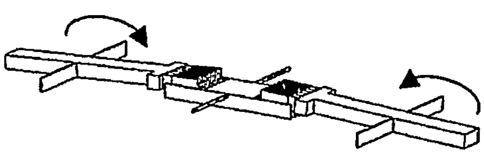

Fig. 1a: Elevation of stator using angular motion

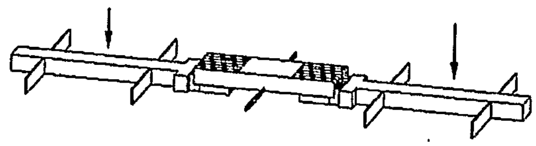

Fig. 1b: Parallel lowering of stators

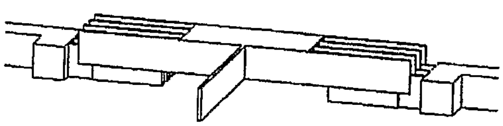

Fig. 2: "Non-Linear" axis of rotation

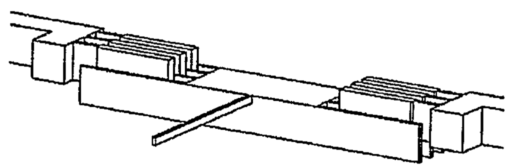

Fig. 3a: Linear angular VCD with lowered stator

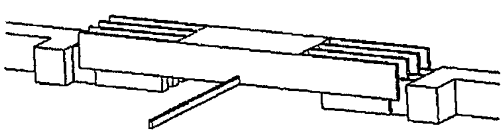

Fig. 3b: Linear angular VCD with elevated stator

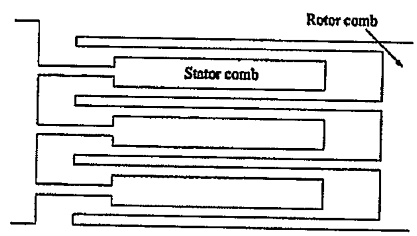

Fig. 4: Thickenning of stator comb

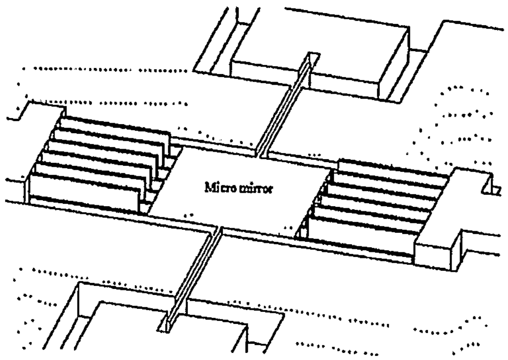

Fig.5: Unloaded position of micro mirror. The suspension is not in contact with stoppers.

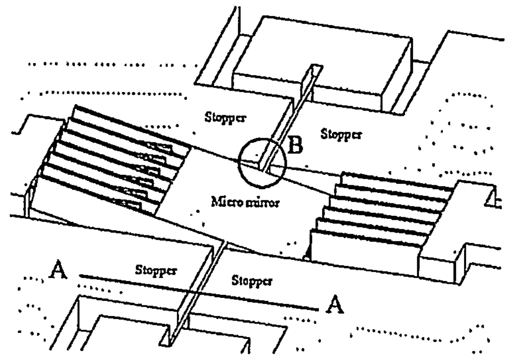

Fig.6a: Maximum tilt angle. The suspension is in contact with the stoppers.

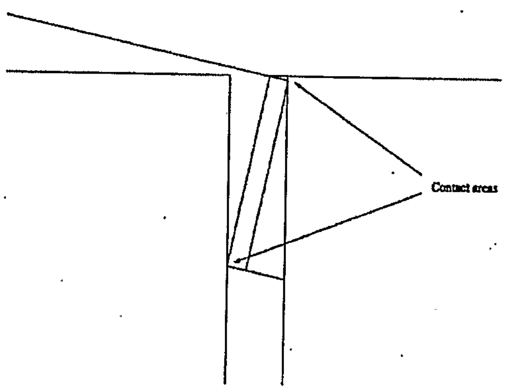

Fig.6b: Suspension contacts at max. tilt angles. (A-A cut view)

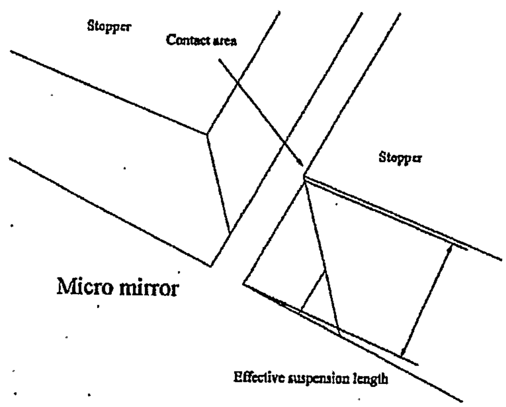

Fig. 7: Zoom in of region B. Effective suspension length.